Lecture 6

Actuators

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ECE 6095/4121
Digital Control of Mechatronic Systems

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Actuators

- Actuator
  - A mechanical device for moving or controlling something
  - Converts electrical/fluid/pneumatic/fuel energy into mechanical energy
- Continuous- and Incremental-Drive Actuators
  - DC Motors …. used in precision position control applications
  - Stepper Motors …. Digital actuator used in position control applications
  - Induction Motors (done in Lecture 1) } used in high-power applications (Not discussed)
  - Synchronous Motors }
  - Hydraulic Actuators
  - Fluidics (Not discussed)
  - Piezo Actuators (Not discussed)

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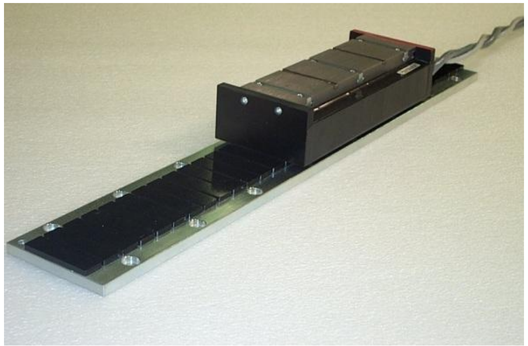
Motors

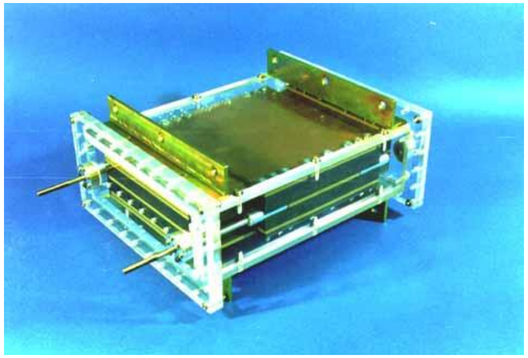
- Motors convert electrical energy to mechanical energy
- Motors make things move



Linear Motor

DC Brush Motor

Induction Motor



Electrostatic Moto

Stepper Motor

Universal Motor

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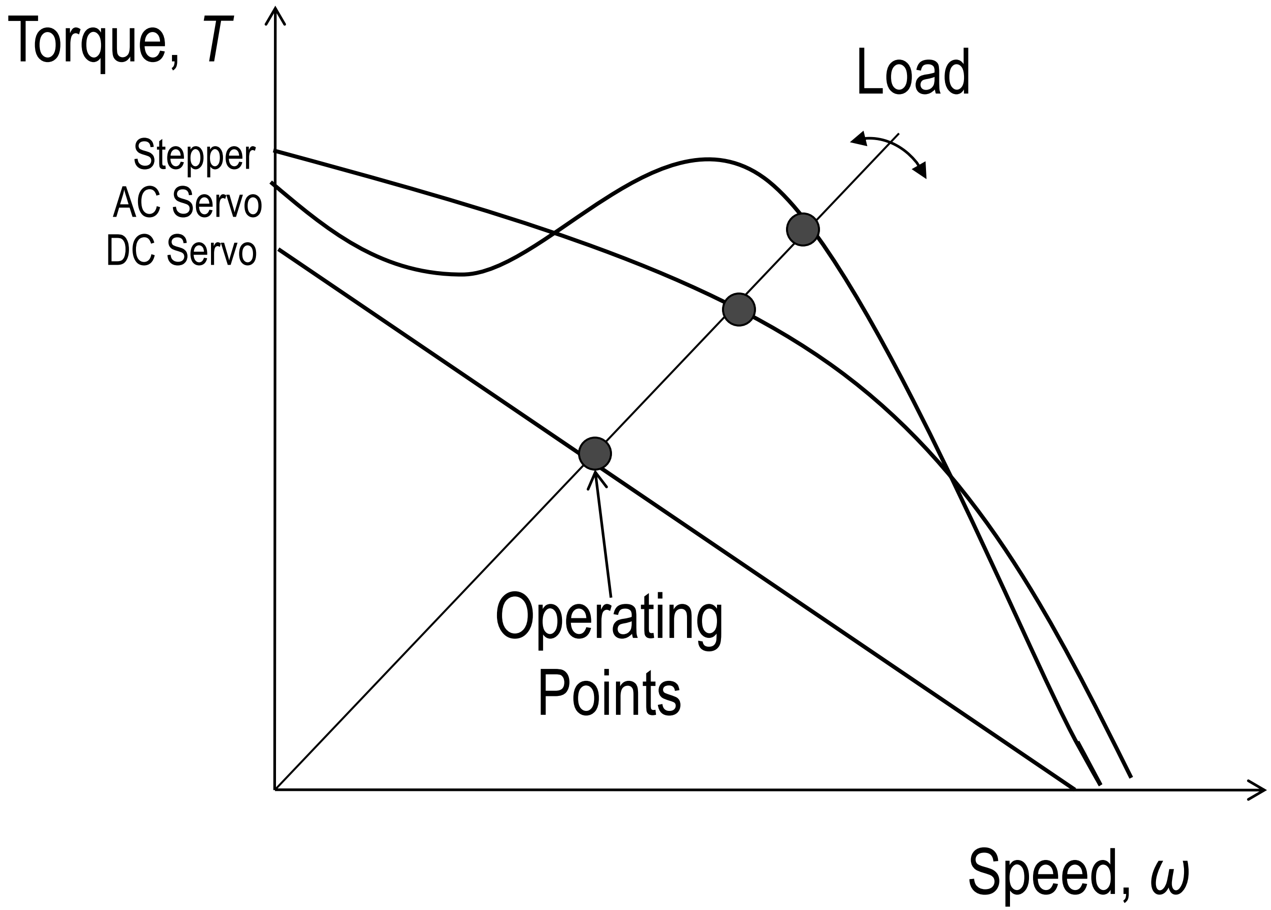
Typical Torque-speed curves



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DC Motors

- DC Motor
  - Most common actuator
  - Converts electrical energy into mechanical energy
  - Motors require more battery power (i.e., current) than electronics (e.g., CPU)
    - e.g., 5 milliamps for the 68HC11 processor vs. 100 milliamps – 1 amp for a small DC motor.
  - Recall Torque ∝ armature current and steady-state torque-speed characteristics of an armature controlled DC motor (constant field current, separately excited)

$$\dot{\theta} = \omega = \frac{v_i - R_A i_A}{K_v}$$

$$T_m = K_T i_A = K i_f i_A$$

$$K_T = K_v = K i_f$$

$$\Rightarrow \omega = \frac{v_i}{K i_f} - \frac{R_A}{(K i_f)^2} T_m$$

$$T_m = 0 \Rightarrow No-load\ speed \Rightarrow \omega_0 = \frac{v_i}{K i_f}$$

$$\omega = 0 \Rightarrow stalling\ torque \Rightarrow T_S = \frac{K i_f v_i}{R_A} \Rightarrow \frac{\omega}{\omega_0} + \frac{T_m}{T_S} = 1$$

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DC Motors

- Positioning ("Servo") Applications
  - Disk-drives, X-Y recorders, instruments, robots, sensor-pointing, fly-by-wire/drive-by-wire inputs, fuel management,sunroof,…
- Speed Control Applications
  - Fans, Drills, CNC machines, window wipers, lifts,…
- Power Range: Few Watts to a few kW
- Speed Range: few rpm to 10000rpm (use gear boxes)
- Time Constant: milli-seconds
- Often in-built encoders for position or tacho for speed
- Digital Control: Pulse-width-modulated (PWM) or Pulse-rate-modulated (PRM)
- When to use a DC Motor?
  - Accurate position/velocity control
  - Low noise
- Limitations: expensive, regular maintenance, heavy

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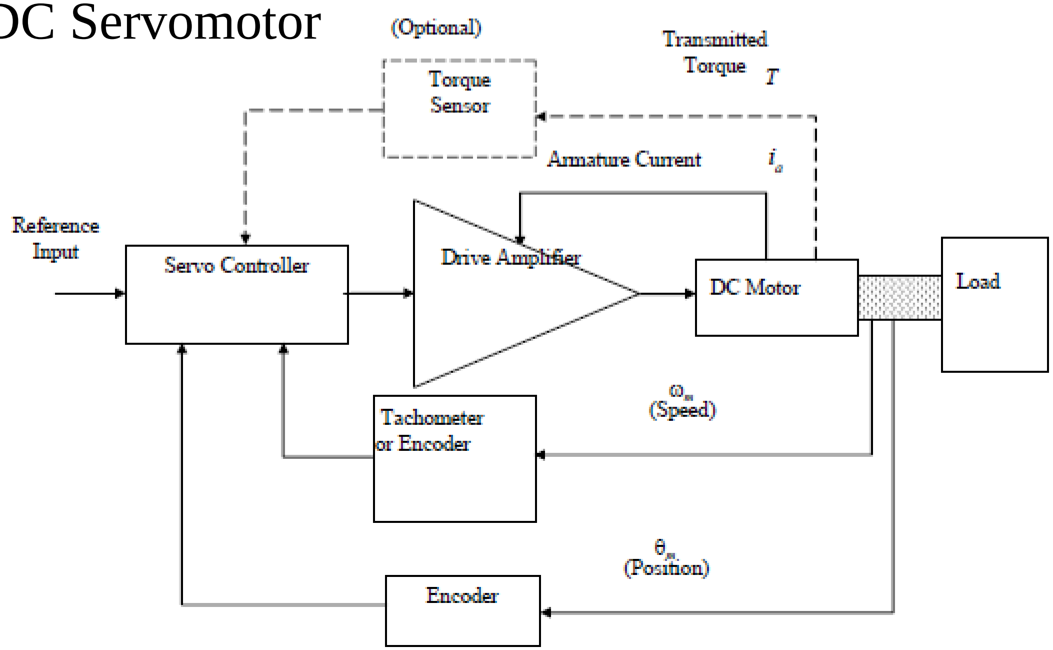
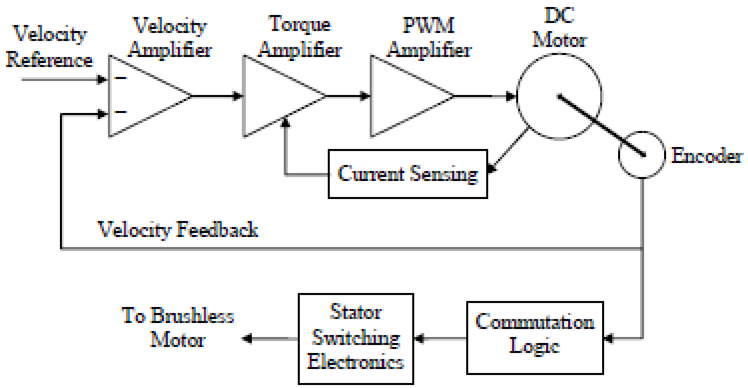
DC Motor Servo and Drive/Control

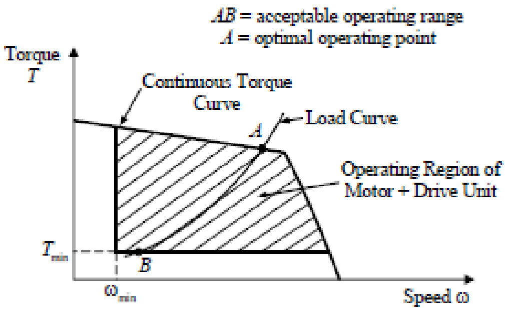
- DC Servomotor



- DC Motor Drive/Control



Motor Selection to Match a Load



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DC Motor Data - 1

- **Mechanical data**
  - Peak torque (e.g., 65 N.m)
  - Continuous stall torque (e.g., 25 N.m)
  - Friction torque (e.g., 0.4 N.m)
  - Maximum acceleration at peak torque (e.g., 33´103 rad/s^2)
  - Maximum speed or no-load speed (e.g., 3,000 rpm.)
  - Rated speed or speed at rated load (e.g., 2,400 rpm.)
  - Rated output power (e.g., 5100 W)
  - Rotor moment of inertia (e.g., 0.002 kg/m^2)
  - Dimensions and weight (e.g., 14 cm diameter, 30 cm length, 20 kg)
  - Allowable axial load or thrust (e.g., 230 N)
  - Allowable radial load (e.g., 700 N)
  - Mechanical (viscous) damping constant (e.g., 0.12 N.m/krpm)
  - Mechanical time constant (e.g., 100 ms)
- **Electrical data**
  - Electrical time constant (e.g., 2 ms)
  - Torque constant (e.g., 0.9 N.m/A for peak current or 1.2 N.m/A rms current)
  - Back emf constant (e.g., 0.95 V/rad/s for peak voltage)
  - Armature/field resistance and inductance (e.g., 1.0 Ω, 2 mH)
  - Compatible drive unit data (voltage, current, etc.)
- **General data**
  - Brush life and motor life (e.g., 5x10^8 revolutions at maximum speed)
  - Operating temperature and other environmental conditions (e.g., 0 to 40 °C)
  - Thermal resistance (e.g., 1.5 °C/W)
  - Thermal time constant (e.g., 70 minutes)
  - Mounting configuration

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DC Motor Data - 2

Motor Data

Line No.	Parameter	Symbol	Units	8X22	8X23	8X24
17	Continuous Torque (Max.)[3]	T_C	oz·in (N·m)	1.6 (11.2×10^{-3})	2.0 (14.1×10^{-3})	2.6 (18.5×10^{-3})
18	Peak Torque (Stall)	T_{PK}	oz·in (N·m)	7.4 (52.0×10^{-3})	10.5 (74.2×10^{-3})	16.8 (118.6×10^{-3})
19	Motor Constant	K_M	oz·in/√W (N·m/√W)	1.12 (7.9×10^{-3})	1.30 (9.2×10^{-3})	1.49 (710.5×10^{-3})
20	No-Load Speed	S_0	rpm (rad/s)	7847 (822)	8298 (869)	10158 (1064)
21	Friction Torque	T_F	oz·in (N·m)	0.35 (2.5×10^{-3})	0.35 (2.5×10^{-3})	0.35 (2.5×10^{-3})
22	Rotor Inertia	J_M	oz·in·s^2 (kg·m^2)	1.4×10^{-4} (9.89×10^{-7})	1.7×10^{-4} (1.20×10^{-6})	2.3×10^{-4} (1.62×10^{-6})

Model GM8XX2 Winding Data (Other windings available upon request)

Line No.	Parameter	Symbol	Units	GM8X22			
34	Reference Voltage	E	V	12.0	19.1	24.0	30.3
35	Torque Constant	K_T	oz·in/A (N·m/A)	1.94 (13.7×10^{-3})	3.07 (21.7×10^{-3})	3.88 (27.4×10^{-3})	4.88 (34.5×10^{-3})
36	Back-EMF Constant	K_E	V/krpm (V/rad/s)	1.43 (13.7×10^{-3})	2.27 (21.7×10^{-3})	2.87 (27.4×10^{-3})	3.61 (34.5×10^{-3})
37	Resistance	R_T	Ω	3.10	7.61	12.1	19.1
38	Inductance	L	mH	1.57	3.93	6.27	9.92
39	No-Load Current	I_{NL}	A	0.25	0.16	0.12	0.10
40	Peak Current (Stall)[4]	I_P	A	3.88	2.51	1.99	1.59

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Drive Amplifier and Power Supply Selection

- Suppose want to select ratings (current, voltage, power) of PWM amplifier and power supply
- Process
  - Required motor torque:

$$T_m = J_m(\dot{\omega})_{max} + T_L + T_f + T_d;\ \text{For pure inertial loads, } T_L = J_L(\dot{\omega})_{\max}$$

  - T_L = worst case load torque; T_f = static friction torque; T_d = damping torque
  - Required current

$$I_A = \frac{T_m}{K_T};\ K_T = \text{ Torque constant of the motor}$$

  - Required voltage

$$v_{i,required} = K_e\ \omega_{\max} + R_A i_A;\ K_e = \text{ Motor EMF constant; } R_A = \text{Armature resistance}$$

  - Voltage Rating

$$v_{i,rating} = \frac{v_{i,required}}{\text{Max duty cycle of PWM Amplifier}}$$

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DC Motor Analysis Example

- For a GR12 C motor, determine the terminal voltage (v_i) for GR12C DC motor to produce a torque of 75 Ncm at 2000 rpm.

DATA TABLES FOR MOTORS

Motor Constants		GR12C	GR12CH	GR16C	GR16CH	GR19CH
Torque	K_t Ncm/Amp	10.8	17.0	23.7	37.3	24.0
EMF	K_e V/krpm	11.3	17.8	24.8	39.0	25.0
Damping	K_d Ncm/krpm	1.16	1.95	3.57	6.44	7.76
Friction Torque	T_f Ncm	4.2	4.2	7.7	7.7	9.8
Terminal Resistance @ 5A	R_m Ohm	0.95	0.95	0.95	0.95	0.65
Rotor Moment of Inertia	J kg.cm^2	1.2	1.2	5.93	5.93	12.71

$$T_{Load} = 75Ncm; T_d = 1.16*2 = 2.32Ncm; T_f = 4.2Ncm$$

$$T_m = T_{Load} + T_d + T_f = 81.52Ncm$$

$$T_m = K_T i_A \Rightarrow i_A = \frac{81.52}{10.8} = 7.55A$$

$$\omega = 209.33 = \frac{v_i - 0.95*7.55}{(11.3/104.67)} \Rightarrow v_i = 29.77V$$

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Series DC Motors - 1

- Series DC motors have armature and field winding in series
  - Field current = Armature current

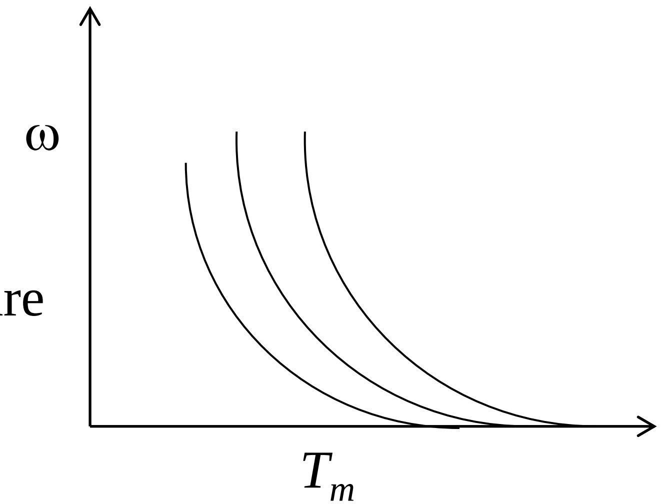
$$\dot{\theta} = \omega = \frac{v_i - (R_A + R_F) i_A}{K' i_A} = \frac{v_i}{K' i_A} - \frac{(R_A + R_F)}{K'}$$

$$T_m = K i_A^2 \Rightarrow i_A = \sqrt{\frac{T_m}{K}}$$

$$\Rightarrow \omega = \frac{v_i}{K'} \sqrt{\frac{K}{T_m}} - \frac{(R_A + R_F)}{K'}$$

Speed of a series motor is inversely proportional to the square root of Torque. Nearly constant power is possible.

- No load speed is infinite
- Speed regulation is poor
- Starting torque and low speed operation are satisfactory



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Series DC Motors - 2

- Example
  - 30kW mechanical power and 250 V supply. Speed is 800 rpm.
  - If load torque is reduced to 200 Nm, what is the new speed?

$$Motor\ current,\ I_A = \frac{Power}{Voltage} = \frac{30,000}{250} = 120\,Amps$$

$$Torque = \frac{Power}{Speed\ in\ rad/\sec} = \frac{30,000}{(800/60).2\pi} = 358.1\,Nm$$

$$Torque = K\ I_A^2 \Rightarrow K = \frac{358.1}{(120)^2} = 0.0249\,Nm/A^2$$

$$With\ the\ new\ load\ torque\ of\ 200\,Nm,\ I_A = \sqrt{\frac{T_m}{K}} = 89.62\ Amps$$

$$Input\ \ power = VI_A = 22.406kW$$

$$Speed\ in\ rad/\sec = \frac{Power}{Torque} = \frac{22,406}{200} = 112.03\,rad/\sec$$

$$Speed\ in\ rpm = 112.03 * 2\pi = 1070.3\,rad/\sec$$

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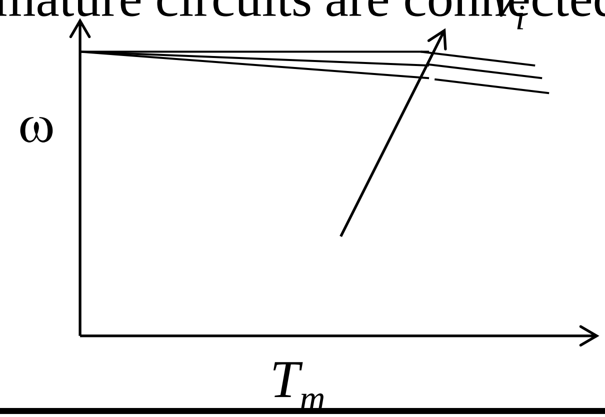
Shunt DC Motors

- In shunt DC motors, both field and armature circuits are connected to the same voltage source



$$i_f = \frac{v_i}{R_f}$$

$$\dot{\theta} = \omega = \frac{v_i - R_A i_A}{K' i_f} = \frac{R_f}{K'} - \frac{R_f R_A i_A}{K' v_i}$$

$$T_m = K i_f i_A \Rightarrow i_A = \frac{T_m R_f}{K v_i}$$

$$\Rightarrow \omega = \frac{R_f}{K'} - \frac{R_f^2 R_A}{K' K v_i^2} T_m$$

$$(i) i_f = \frac{v_i}{R_f} = \frac{500}{500} = 1A; i_A = 21 - 1 = 20A$$

$$v_b = v_i - R_A i_A = 480V; Power = T_m \omega = 480 * 20 = 9600W$$

$$\omega = 96 rad/\sec \Rightarrow 916.7 rpm$$

$$(ii) K i_f = K = \frac{100}{20} = 5Nm/A \Rightarrow i_A = \frac{120}{5} = 24A$$

$$v_b = v_i - R_A i_A = 476V; Power = T_m \omega = 476 * 24 = 9600W$$

$$\omega = 95.2 rad/\sec \Rightarrow 909.6 rpm$$

- Very good speed regulation and high starting torque
- Example: Shunt DC motor with 500V supply, $R_A = 1\ \Omega$, $R_F = 500\ \Omega$. Find the speed when the motor draws 21A current and load torque is 100 Nm. If load torque is changed to 120Nm, what is the new speed?

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Compound DC Motors

- In compound DC motors, part of field winding is in series (R_{f1}) and the rest is in parallel (R_{f2})

$$i_f = i_{f1} + i_{f2} = i_A + \frac{v_i}{R_{f2}}$$

$$\dot{\theta} = \omega = \frac{v_i - (R_A + R_{f1})i_A}{K' i_f} = \frac{R_f}{K'} - \frac{R_f R_A i_A}{K' v_i}$$

$$T_m = K i_f i_A \Rightarrow T_m = K i_A^2 + K \frac{v_i}{R_{f2}} i_A$$

$$\Rightarrow i_A^2 + \frac{v_i}{R_{f2}} i_A - \frac{T_m}{K} = 0 \Rightarrow i_A = \frac{1}{2}\left(-\frac{v_i}{R_{f2}} + \sqrt{\left(\frac{v_i}{R_{f2}}\right)^2 + 4\frac{T_m}{K}} \right)$$

$$\Rightarrow \omega = \frac{2v_i - (R_A + R_{f1})\left(-\frac{v_i}{R_{f2}} + \sqrt{\left(\frac{v_i}{R_{f2}}\right)^2 + 4\frac{T_m}{K}} \right)}{K'\left(\frac{v_i}{R_{f2}} + \sqrt{\left(\frac{v_i}{R_{f2}}\right)^2 + 4\frac{T_m}{K}} \right)}$$

Provides trade-off in Performance between series and shunt DC motor s

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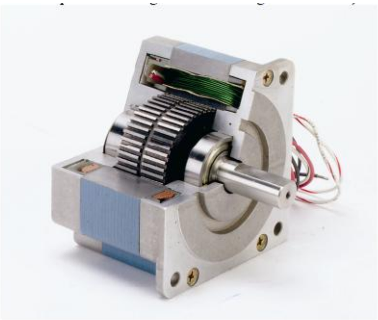
Stepper Motors

- Stepper motors are accurate pulse-driven motors that change their angular position in steps, in response to input pulses from digitally controlled systems
- The stepper motor makes a step for each applied pulse
- The size of the step (step angle) depends on the type and design of the stepper motor
- The input pulses to the stepper motor must be in a proper sequence with acceptable frequency and must provide the phase windings with sufficient current
- Typical applications of stepper motors requiring incremental motion are printers, disk drives, robotics, X-Y plotters.



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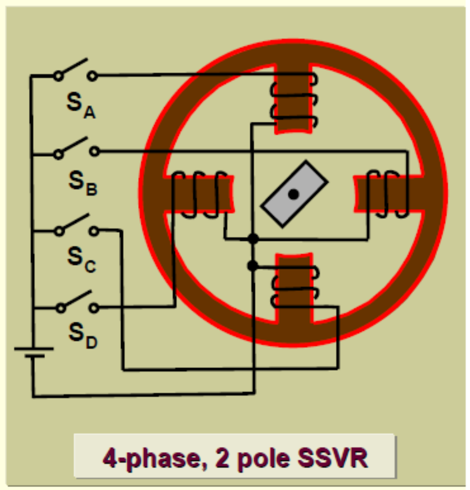
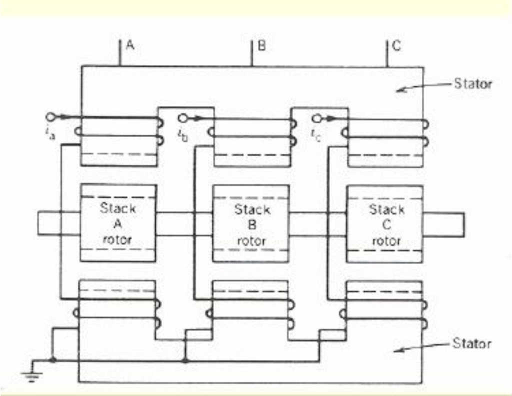
Stepper Motor Basics

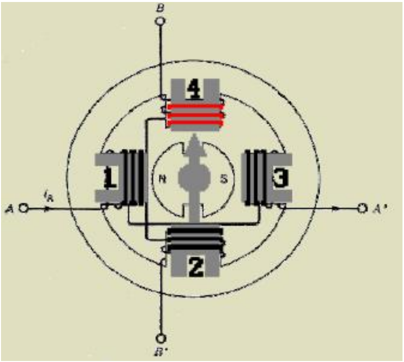
- So, Stepper Motors
  - Are driven in fixed angular steps
  - Each rotation step = rotor response to an input pulse (or a digital command)
- Three Basic Types
  - Variable reluctance stepper motors (have soft iron core; single/multi-stack)
  - Permanent Magnet stepper motors (have magnetized rotors)
  - Hybrid stepper motors (have two stacks of rotor teeth forming the two poles of a permanent magnet located along the rotor axis).



Variable Reluctance (single stack)



3-stack VR stepper motor



2-pole PM stepper motor

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When do you use which Stepper Motor?

- VR Stepper Motor
  - Small step sizes
  - Typically smaller torque
- PM Stepper Motor
  - Larger step sizes (30-90 degrees)
  - Have higher inertia and slower acceleration
  - More torque per ampere of stator current than VR stepper motor
- Hybrid Stepper Motor
  - Smaller step sizes
  - More torque than VR stepper motor
  - Natural choice for applications requiring small step length and high torque
  - More expensive than a VR stepper motor

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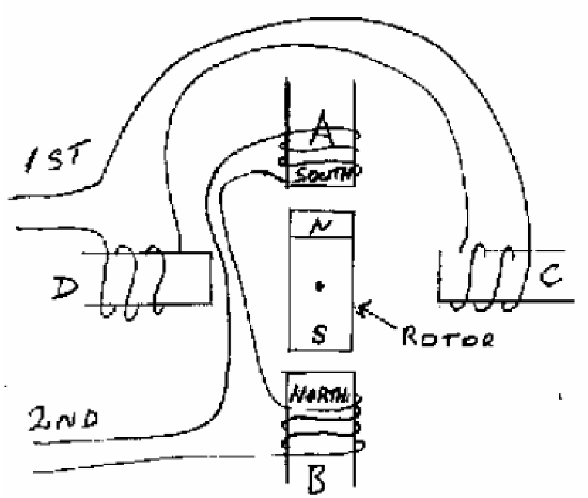
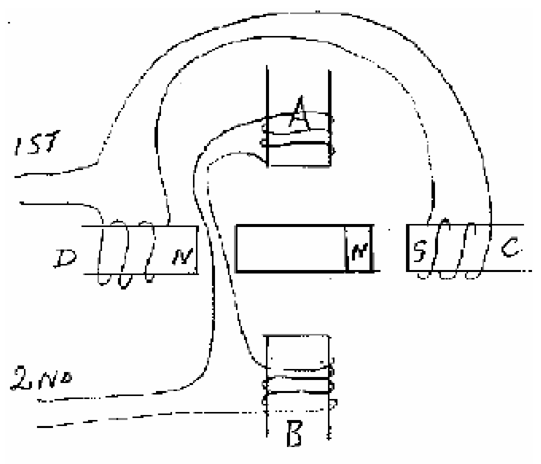
Basic Stepper Motor Concepts



4 wires



- Rotor is a magnetic bar that pivots about its center
- Each loop forms an electromagnet with different polarity
- If we apply a voltage to loop 2 such that pole piece A is South and B is North (it must be because of the way they are wound), the rotor magnet will line up as shown. This is called holding position
- If we remove the voltage from the second loop and apply it to the first loop, pole pieces A and B will have no magnetic attraction and pole pieces C and D will have
- The rotor will turn, so the magnet will take up a new position and be rotated 90 degrees clock wise

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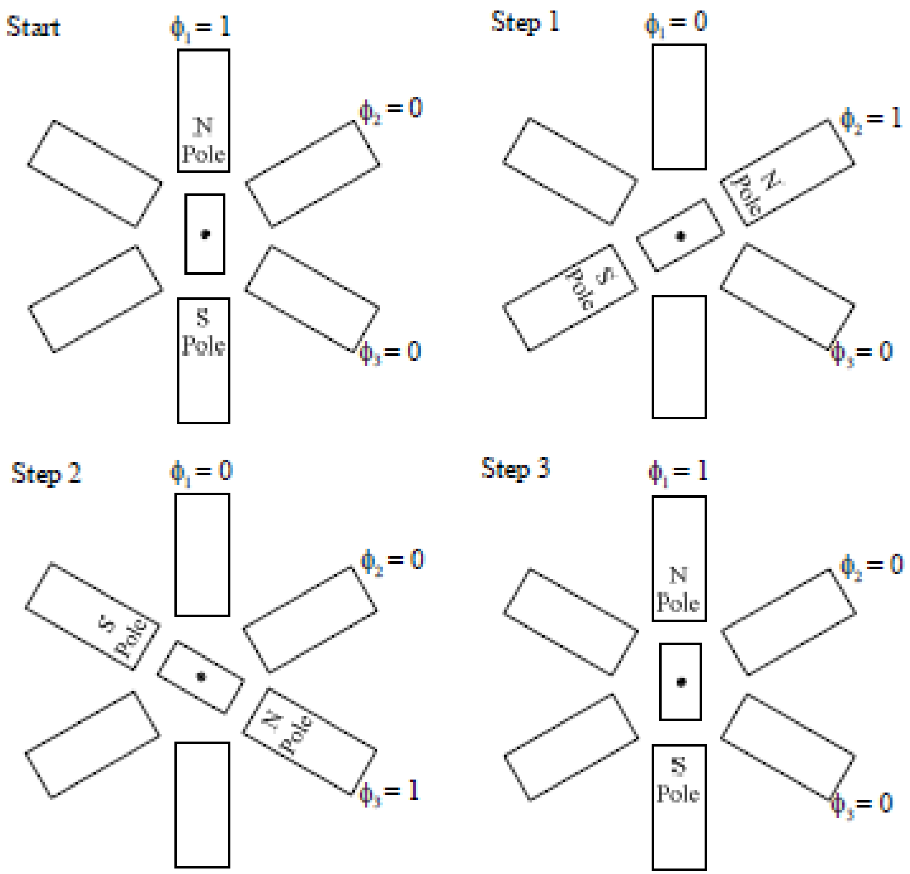
Full-stepping Sequence for a 3-ϕ VR Stepper Motor



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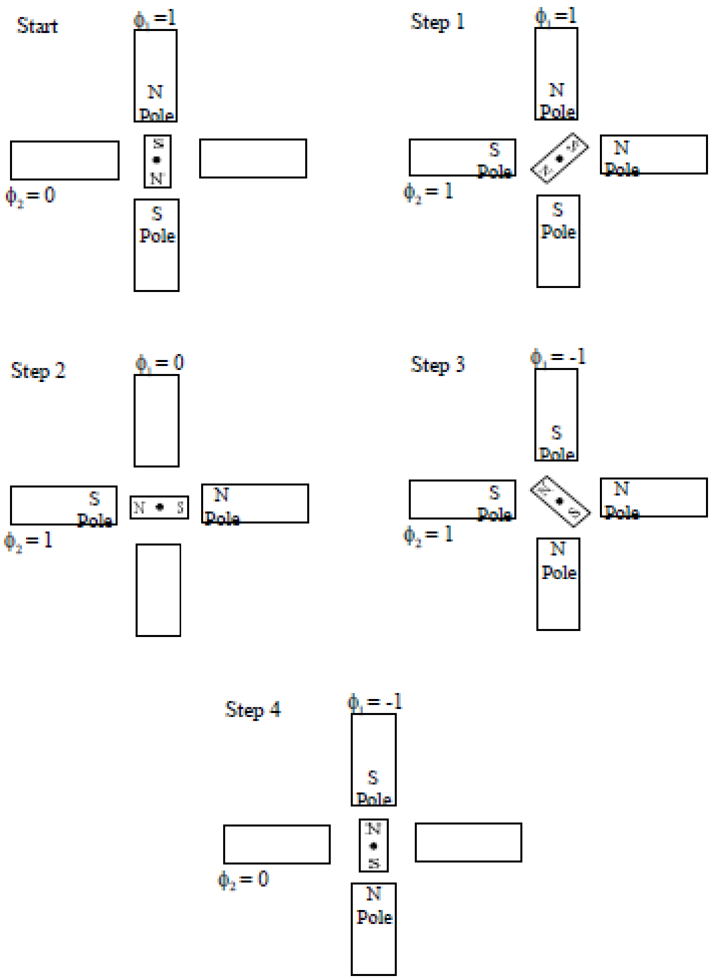
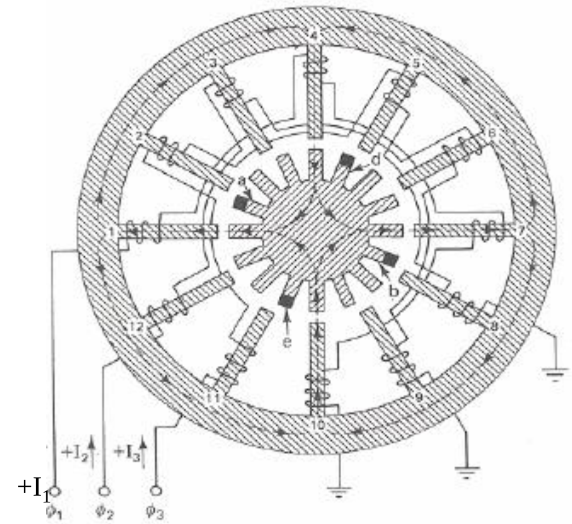
Half-stepping Sequence for a 2-ϕ Stepper Motor



$$\pm\frac{1}{mN_r} = \frac{1}{N_s} - \frac{1}{N_r} \Rightarrow N_r = N_s\left(1 \pm \frac{1}{m}\right)$$



- If the stator has N_s poles, stator pole pitch is 360/ N_s degrees
  - $N_s = 12 \Rightarrow$ stator pitch = 30^0
- If number of rotor poles is N_r, rotor pitch is 360/ N_r degrees
  - $N_r = 16 \Rightarrow$ rotor pitch = 22.5^0
- Step angle = 360 (1/ N_s - 1/ N_r)
- Number of phases = m; (N_s/m even)
- Need : $\pm 360/m\, N_r = 360\,(1/N_s - 1/N_r)$

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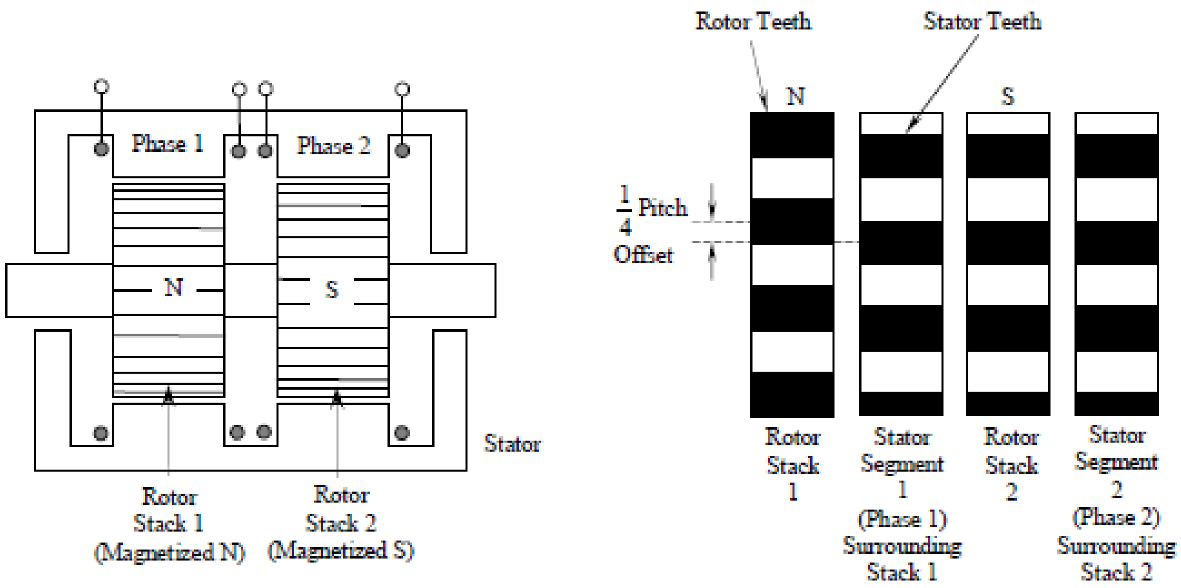
Hybrid Stepper Motor



- Rotor stack misalignment (1/4 pitch) in a hybrid stepper motor
- Schematically shows the state where phase 1 is off and phase 2 is on with N polarity

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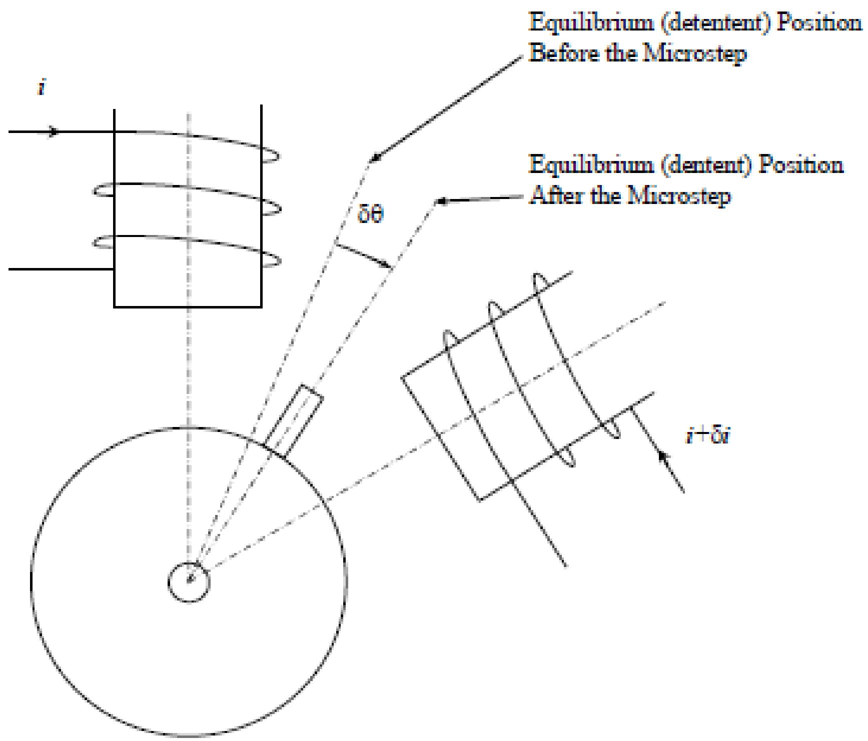
Micro-stepping



- Rotor stack misalignment (1/4 pitch) in a hybrid stepper motor
- Schematically shows the state where phase 1 is off and phase 2 is on with N polarity

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Stepper Motor Spec Sheet

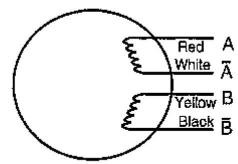
JAMECO
ELECTRONIC COMPONENTS
COMPUTER PRODUCTS

Part No. 117954
Product No. LB82773-M1
2 Phase Bipolar Stepper Motor

1355 Shoreway Rd., Belmont, CA 94002 • Tel: 415-592-8097 • Fax: 415-592-2503 • BBS: 415-637-9025

Specifications:

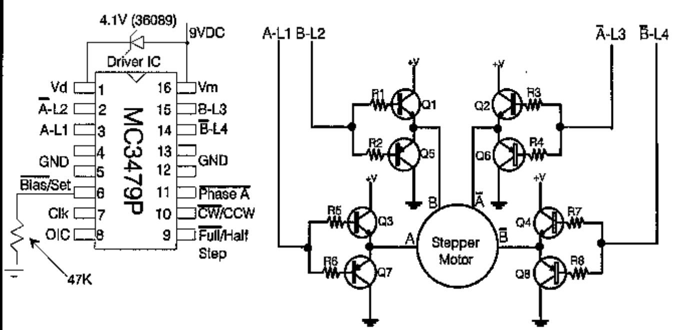
- Bipolar (2 Phase)
- 5VDC, 800mA
- Coil: 6.25 Ohm
- 7.5 degrees/step
- Shaft: 0.250"D x 0.75"L
- Mounting Hole Spacing: 2.60"
- Mounting Hole Diameter: 0.20"
- Motor: 2.25"D x 0.99"H
- Detent Torque: 100 g-cm
- Holding Torque: 1080 g-cm
- Weight: 0.61 lbs.



Step	A	B	Ā	B̄
1	+	+	-	-
2	-	+	+	-
3	-	-	+	+
4	+	-	-	+
5	+	+	-	-

Applications:

- Automation
- Robotic Control
- Precision Mechanical Control



Q1-Q4 = MJE3055T (25857)
Q5-Q8 = MJE2955T (25831)
R1-R8 = 1K (29663)
Driver IC - MC3479P (25216)
021795JC

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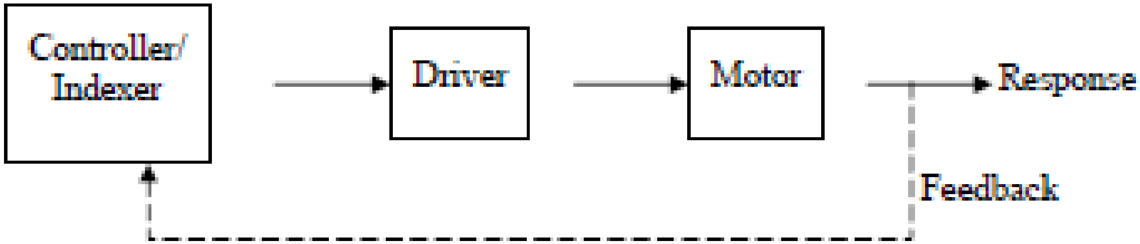
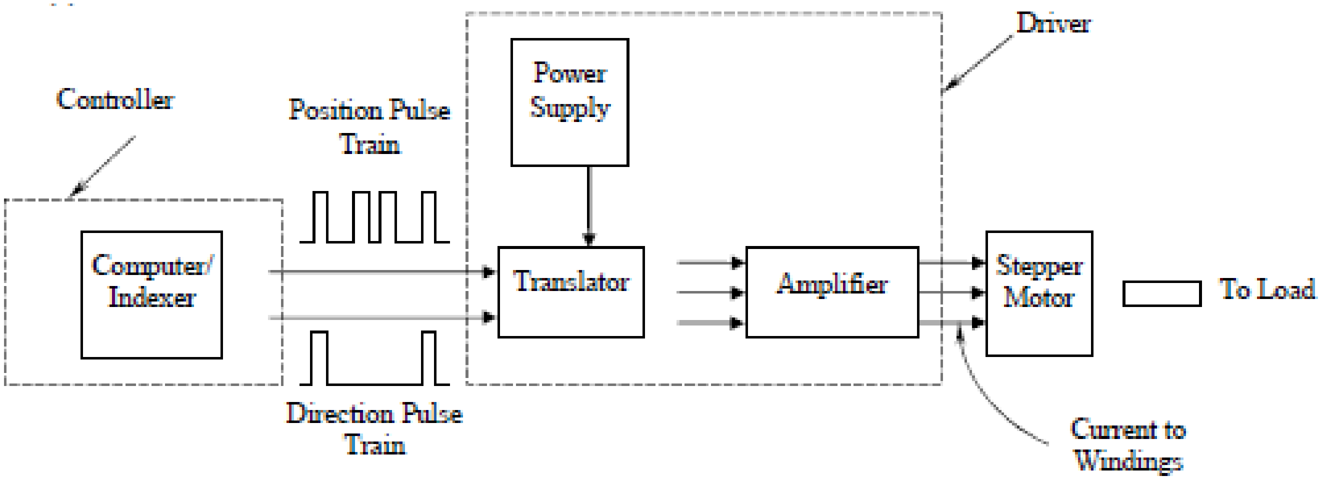
Stepper Motor Drive System





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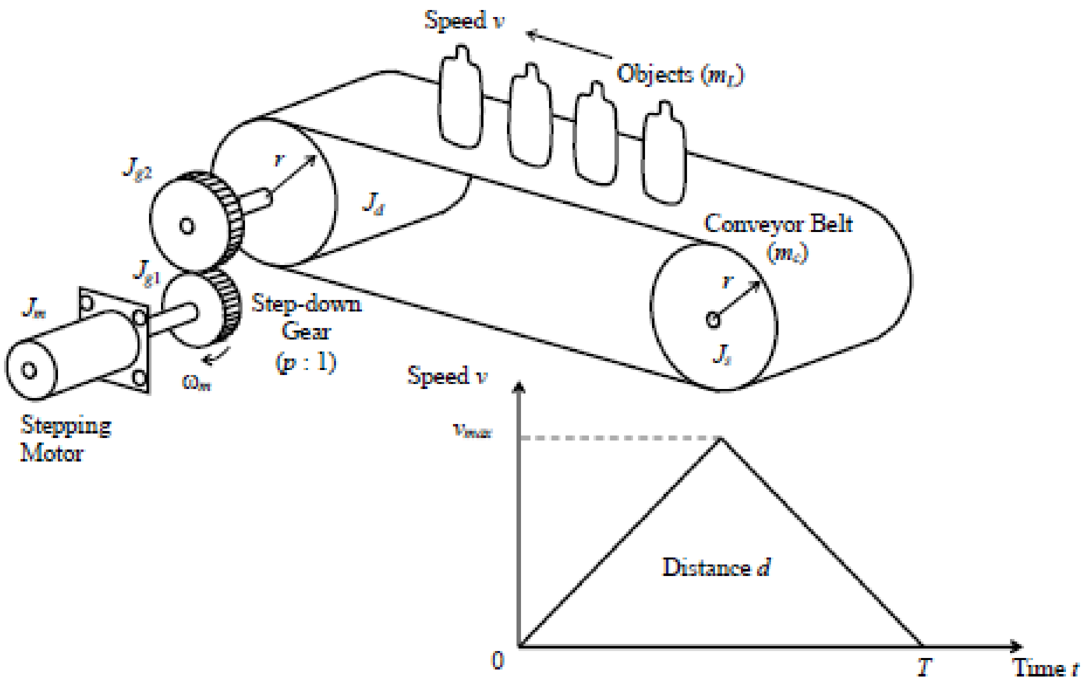
Stepper Motor Selection Example - 1



- Equivalent Inertia at Rotor of the Motor via overall Kinetic Energy

$$KE = \frac{1}{2}(J_m + J_{g1})\omega_m^2 + \frac{1}{2}(J_{g2} + J_d + J_s)\left(\frac{\omega_m}{p}\right)^2 + \frac{1}{2}(m_c + m_L)\left(\frac{r\omega_m}{p}\right)^2 = \frac{1}{2}J_e\omega_m^2$$

$$\Rightarrow J_e = J_m + J_{g1} + \left(\frac{1}{p}\right)^2 (J_{g2} + J_d + J_s) + \left(\frac{r}{p}\right)^2 (m_c + m_L)$$

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Stepper Motor Selection Example - 2

- Data

$$d = 10\ cm,\ T = 0.2\ \sec;\ r = 10\ cm;\ m_c = 5\ kg;\ m_L = 5\ kg,;\ J_d = J_s = 2.0\text{x}10^{-3}\ kg.m^2$$

$$Two\ gear\ units:\ p = 2\ and\ 3;\ J_{g1} = 50\text{x}10^{-6}\ kg.m^2\ and\ J_{g2} = 200\text{x}10^{-6}\ kg.m^2$$

$$Overall\ system\ efficiency = 80\%\ (for\ either\ gear\ unit)$$

- From triangular speed profile:

$$d = \frac{1}{2} v_{\max} T \Rightarrow v_{\max} = \frac{2d}{T} = \frac{0.2}{0.2} = 1\, m/\sec$$

- Max acceleration/deceleration

$$a_{\max} = \frac{v_{\max}}{(T/2)} = 10\, m/\sec^2$$

- Maximum angular acceleration/deceleration and max. velocity of motor

$$\dot{\omega}_{\max} = \frac{p a_{\max}}{r} = 100 p\ rad/\sec^2;\quad \omega_{\max} = \frac{p v_{\max}}{r} = 10 p\ rad/\sec$$

- Maximum Torque needed with a motor of efficiency, η

$$\eta T_m = \left(J_m + J_{g1} + \left(\frac{1}{p}\right)^2 (J_{g2} + J_d + J_s) + \left(\frac{r}{p}\right)^2 (m_c + m_L) \right) \frac{p a_{\max}}{r}$$

$p = 1$ when no gears

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Stepper Motor Selection Example - 3

- Stepper Motor Specifications

MODEL		50SM	101SM	310SM	1010SM
NEMA Motor Frame Size		23		34	42
Full Step Angle	degrees	1.8			
Accuracy	percent	±3 (noncumulative)			
Holding Torque	oz-in	38	90	370	1050
	N-m	0,27	0,64	2,61	7,42
Detent Torque	oz-in	6	18	25	20
	N-m	0,04	0,13	0,18	0,14
Rated Phase Current	Amps	1	5	6	8.6
Rotor Inertia	oz-in-sec^2	1.66×10^{-3}	5×10^{-3}	26.5×10^{-3}	114×10^{-3}
	kg-m^2	$11{,}8 \times 10^{-6}$	35×10^{-6}	187×10^{-6}	805×10^{-6}
Maximum Radial Load	lb	15		35	40
	N	67		156	178
Maximum Thrust Load	lb	25		60	125
	N	111		267	556
Weight	lb	1.4	2.8	7.8	20
	kg	0,6	1,3	3,5	9,1
Operating Temperature	°C	-55 to +50			
Storage Temperature	°C	-55 to +130			

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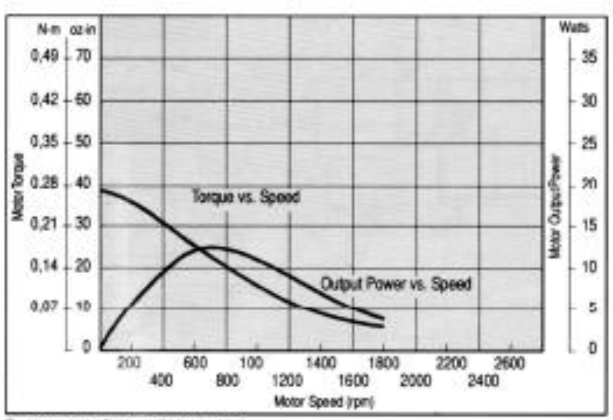
Stepper Motor Selection Example - 4

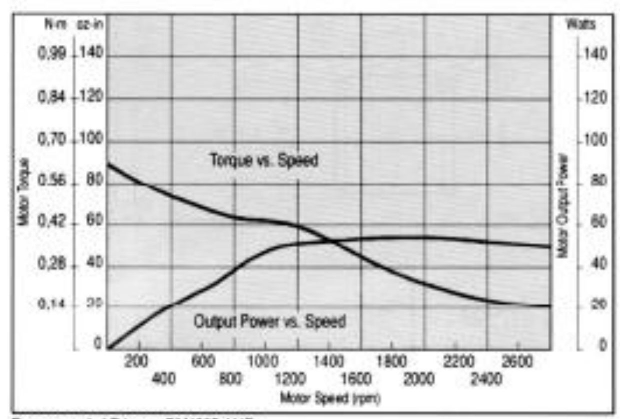
- Stepper Motor Performance Curves

Model 50SM



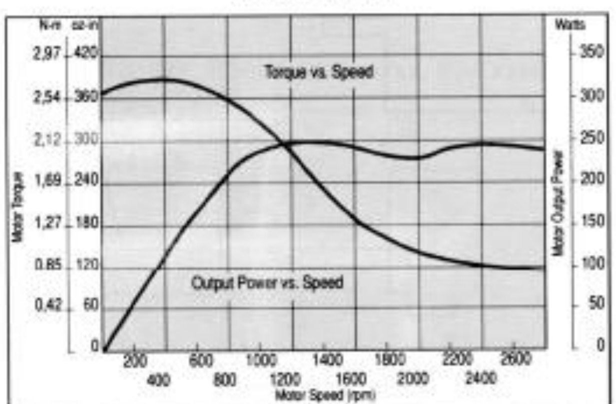
Recommended Drivers : DM4001, U1A

Model 101SM



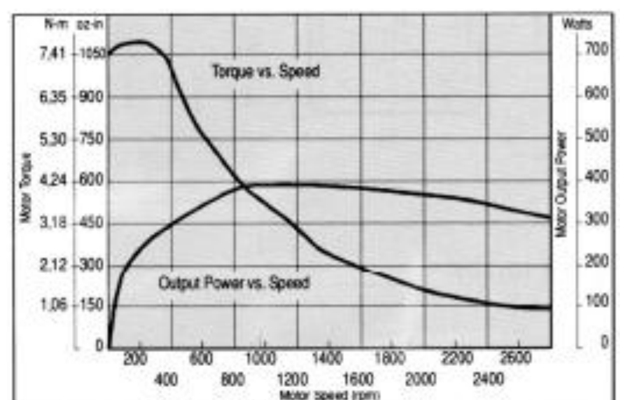
Recommended Drivers: DM4005, U1D

Model 310SM



Recommended Drivers: DM8010, DMV8008, U1D

Model 1010SM



Recommended Drivers: DM16008, DMV16008, U1F

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Stepper Motor Selection Example - 5

- No gear case (p = 1), Efficiency η = 0.8

$$\eta T_m = \left(J_m + J_d + J_s) + (r)^2 (m_c + m_L)\right)\frac{a_{\max}}{r} = \left(J_m + 0.002 + 0.002 + (0.1)^2 (5+5)\right)100$$

$$\Rightarrow T_m = 125(\left(J_m + 0.104\right) N.m;\ \omega_{\max} = 10\ rad/\sec = 95.5\ rpm \Rightarrow \text{operating speed range: 0-95.5}\ rpm$$

- **Note:** Torque at 95.5 rpm is < starting torque for first two motors (see speed-torque curves)
- In motor selection use the weakest point (i.e., lowest torque) in the operating speed range
- Form the following table:

Motor Model	Available Torque at ω_{max} (N.m)	Motor Rotor Inertia (kg.m^2)	Required Torque (N.m)
50 SM	0.26	11.8×10^{-6}	13.0
101 SM	0.60	35.0×10^{-6}	13.0
310 SM	2.58	187.0×10^{-6}	13.0
1010 SM	7.41	805.0×10^{-6}	13.1

Note: Without a gear unit, available motors cannot meet system requirements.

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Stepper Motor Selection Example - 6

- Gear case (p = 2), Assume same efficiency η = 0.8

$$\eta T_m = \frac{p a_{\max}}{r} \cdot \left(J_m + J_{g1} + \left(\frac{1}{p}\right)^2 (J_{g2} + J_d + J_s) + \left(\frac{r}{p}\right)^2 (m_c + m_L) \right)$$

$$= 200. \left(J_m + 50.10^{-6} + \left(\frac{1}{4}\right)(200.10^{-6} + 0.002 + 0.002) + \left(\frac{0.1}{2}\right)^2 (5+5) \right)$$

$$=200.(J_m + 0.0261) \Rightarrow T_m = 250.(J_m + 0.0261)$$

$$\omega_{\max} = 191 rpm$$

- Form the following table:

Motor Model	Available Torque at ω_{max} (N.m)	Motor Rotor Inertia (kg.m^2)	Required Torque (N.m)
50 SM	0.25	11.8×10^{-6}	6.53
101 SM	0.58	35.0×10^{-6}	6.53
310 SM	2.63	187.0×10^{-6}	6.57
1010 SM	7.41	805.0×10^{-6}	6.73

← Select this motor. Has 200 steps

- With full stepping, step angle = 1.8°. Corresponding step in conveyor motion = positioning resolution = (1.8/2)x(π/180)x0.1 = 1.57x10^{-3} m

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Hydraulic Control System - 1

- Typical hydraulic control system
  - Hydraulic fluid (mineral oil or oil in water emulsions) is pressurized using a pump driven by an AC motor
  - The oils have the desirable properties of self-lubrication, corrosion resistance, good thermal properties, fire resistance, environmental friendliness, low compressibility (high stiffness for good bandwidth)
  - Power conversions (typically $\eta_m = 0.9$; $\eta_h = 0.6$)

$$(i,v) \xrightarrow{\eta_m} (T,\omega) \xrightarrow{\eta_h} (Q,P)$$

  - Flow rates in the range of 1,000 to 50,000 gal/min (Note: 1 gal/min = 3.76 L/min) and pressures from 500 to 5000 psi (Note: 1kPa=0.145 psi)
  - Pressure from the pump is regulated and stabilized by a relief valve and an accumulator
  - A hydraulic valve provides a controlled supply of fluid into the actuator, controlling both the flow rate (including direction) and the pressure

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Hydraulic Control System - 2

- Main components of a hydraulic control system
  - Serve valve
  - Hydraulic actuator
  - Load
  - Feedback control elements (sensors and compensation circuitry, servo amplifier, valve actuator
- Valve (incremental changes)

$$q = k_q u - k_c p$$

- Hydraulic Actuator

$$q = A\frac{dy}{dt} + \frac{V}{2\beta}\frac{dp}{dt}$$

- Load

$$m\frac{d^2y}{dt^2} + b\frac{dy}{dt} = Ap - f_L$$

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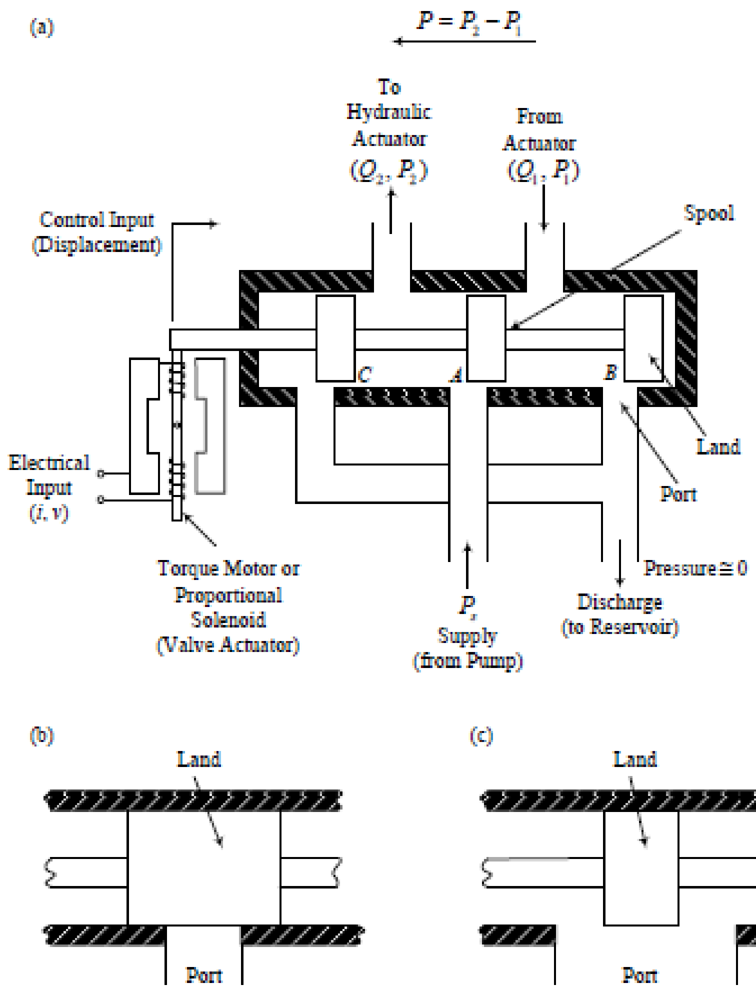
Hydraulic Spool Valve



(a) A four-way spool valve, (b) An overlapped land, (c) An under-lapped land

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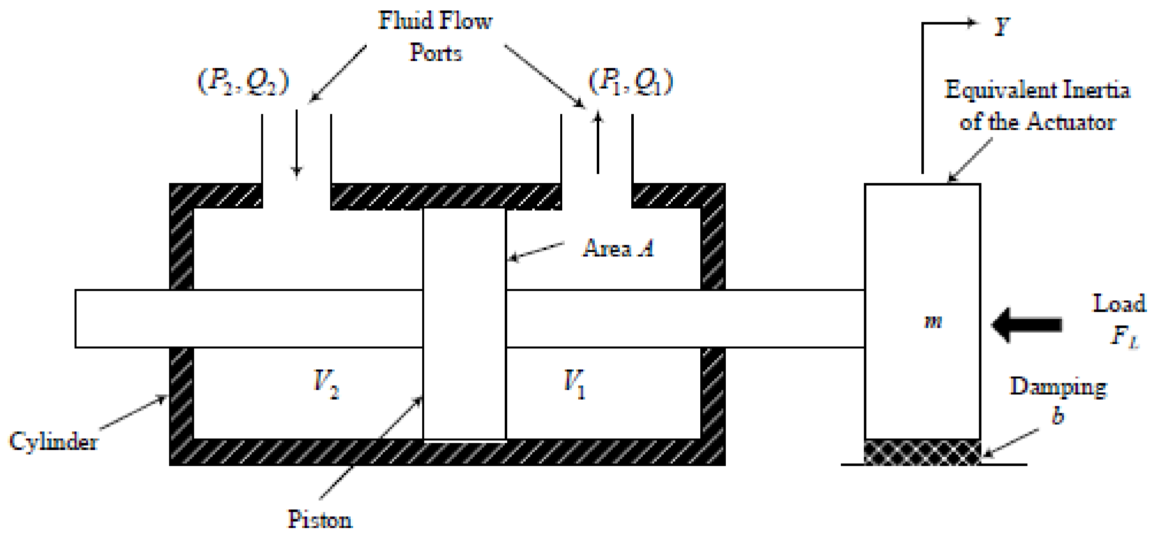
Hydraulic Actuator



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Advantages /Disdvantages of Hydraulic Actuators

- Advantages over Electric Motor Systems
  - High pressures (e.g., 5,000 psi) → Can provide very high forces (torques) at high power levels simultaneously to several actuating locations (flexible)
  - Quite stiff when viewed from load side (because a hydraulic medium is mechanically stiffer than an electromagnetic medium)
  - Heat generated at the load can be quickly transferred to another location away from the load by the hydraulic fluid itself
  - Self-lubricating → Low friction in valves, cylinders, pumps, hydraulic motors, etc.
  - Safety considerations will be less (e.g., no possibility of spark generations unlike motors with brush mechanisms)
- Disadvantages
  - More nonlinear
  - Noisier
  - Synchronization of multi-actuator operations may be difficult
  - More expensive and less portable

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